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Title: Uncertainty Quantification and Sensitivity Analysis for Simulation of Hostile Blast Events

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Uncertainty Quantification and Sensitivity Analysis for Simulation of Hostile Blast Events

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LANL Blast Tube Facility

Outline

- LANL Blast Tube Facility overview
- QUINOA overview
- Sensitivity Analysis
- Aeroshell Analysis
- Conclusions

AirBlast

AirBlast:

- A large shocktube is driven by high explosives
- A re-entry body is placed at mouth of the shock tube
- Pressure sensors record pressure and video trajectory of the body is recorded after shock impact
- We can alter HE package for different strength shocks
- We can alter the orientation (Pitch, roll, etc) of the reentry body

Computational Effort

- Experiments are often expensive, and potentially dangerous with multiple atmospheric variables which can affect results
- We desire a way to simulate these experiments to both verify our numerical tools are working correctly and explore the design space of the experiments more thoroughly.

Simulation needs

Multi-Physics problems:

- HE Physics involves short time scales and burn physics
- Long shock tube involves need for code with good shock physics built-in
- Shock passing over body ideally will yield structural response and coupled body motion
- Large physical scales and very short physical scales requires an expensive compute mesh, so we need a highly parallel capability
- End of tube has mobile rail car that affects reflection front

Quinoa Background

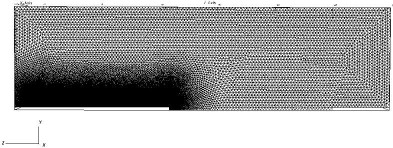
Reasons to use

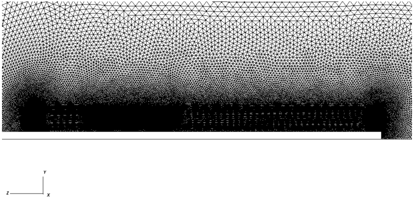
- Massively parallel capability, built on Charm runtime
- Verified extensively and well maintained
- Asynchronous parallel capability and automatic load balancing
- Designed for open flow problems
- Uses built-in Riemann solvers and MUSCL reconstruction, and solves compressible flow physics natively

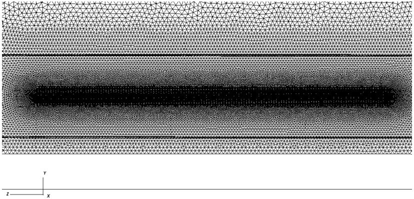
Issues

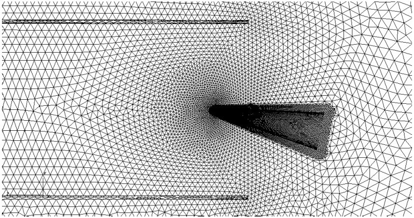
- No HE physics or burn model (JWL EOS and Program Burn now implemented, but not available for most of this study)
- No Fluid Structure Interaction (An overset methodology is under development and near completion)

Numerical setup









Numerical Approach

- Simulations are large and expensive at resolutions necessary to resolve forces over body
  - Approximately 50 wall clock hours on 360 processors
  - This is a nonstarter for a detailed parameter study
- If we can split the mesh into two smaller meshes, one containing the HE portion, and one containing the RB portion, we can explore the design space more efficiently
  - We run a small simulation with just the HE, and use the pressure profile at a slice as a boundary condition for another simulation with just the RB.
  - A high res simulation with just the shock tube took 8 hours on 360 processors.

Numerical Study

We believe we can now run a parameter study by effectively splitting the variables of interest into two categories: HE-centric and RB-centric

- HE-centric includes:
  - Atmospheric conditions (ambient temperature and pressure)
  - Mass of HE
  - **Location/orientation of HE inside tube**
- RB-centric includes:
  - Position of RB
  - Orientation of RB (pitch or roll)

ECMF

- We have ported all model and mesh creation for full, downstream, and upstream simulations to the ECMF
- The ECMF framework allows us to use our quantities of interest as variables during model generation
- We can use LHS to create a spanning set of different orientations and conditions to examine the experimental space

Upstream Study

- No Reentry Body
- Run baseline idealized case that matches experimental reported setup
- Perform mesh convergence study
- Vary HE placement, weight, and atmospheric conditions

Mesh Convergence

Table: Results from grid convergence simulations.

Simulation	Mesh Elements	Shock Speed [ft/s]	Impulse [psi s]	Peak Pressure [psi]
baseline	3.8e6	4711	4965	207
fine	5.7e6	4669	5026	209
extra fine	12.7e6	4646	4948	213
extra extra fine	33.5e6	4629	4986	213

Extremely fine mesh simulations took unacceptably long wall clock times to run ($>$1 day), while yielding less than 3% difference in any of the quantities of interest investigated. This was deemed acceptable, and we proceeded with the remainder of the sensitivity analysis using the baseline mesh.

Vertical offset of HE

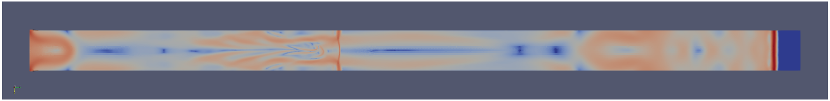
Table: Vertical offset simulations.

Offset [in]	Shock Speed [ft/s]	Impulse [psi s]	Peak Pressure [psi]
0	4797	5002	205
1	4767	5001	204
2	4747	4996	205
3	4728	4991	202
6	4711	4965	207
12	4692	4947	217
24	4626	4978	234

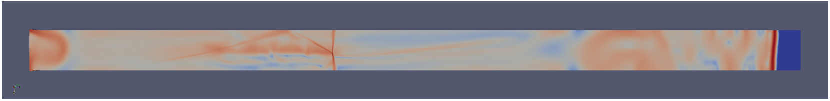
Looking solely at these metrics, it appears minor offsets of < 6 inches do not affect the solution by much at all.

Vertical Offsets

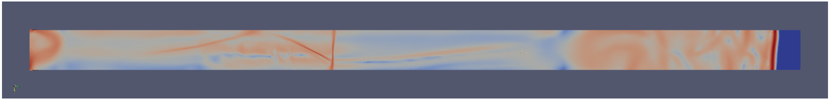
But visual inspection shows something different...



(a) No vertical offset



(b) 3 in vertical offset



(c) 6 in vertical offset

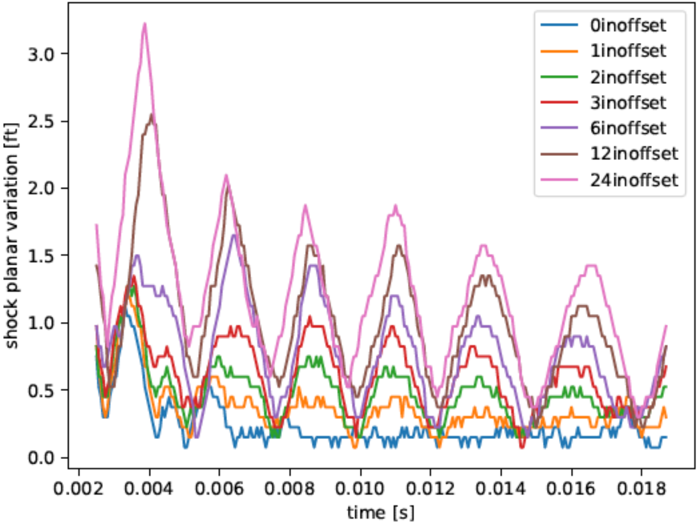
Figure: Snapshots showing density gradients in flowfield at different intial HE offsets, highlighting difference in the shock shape.

Planarity

We need a way to quantify the planarity of the shock

- Is this effect real?
    - Work done with Bayesian Inference modelling in the EQMU toolbox and experimental results suggest that it is.
- How best to quantify it?
    - We measure the foremost position of the shock and the aftmost position of the shock as it progresses down the tube. We can plot the difference.

Planarity



0inoffset
1inoffset
2inoffset
3inoffset
6inoffset
12inoffset
24inoffset
shock planar variation [ft]
0.0
0.5
1.0
1.5
2.0
2.5
3.0
0.002
0.004
0.006
0.008
0.010
0.012
0.014
0.016
0.018
time [s]

Experimental Evidence

Shots CTU3 and CTU1 both show visible evidence of a non planar shock

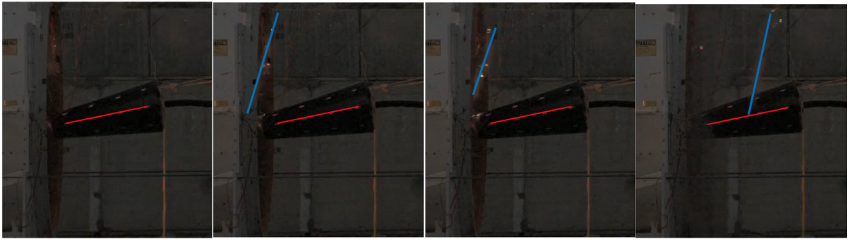


Figure: Time progression of experiment CTU3, angle is ≈12.5°

Experimental Evidence

Shots CTU3 and CTU1 both show visible evidence of a non planar shock

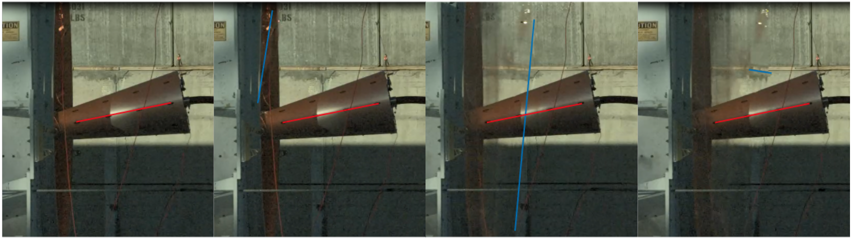


Figure: Time progression of experiment CTU1, angle is ≈7.5°

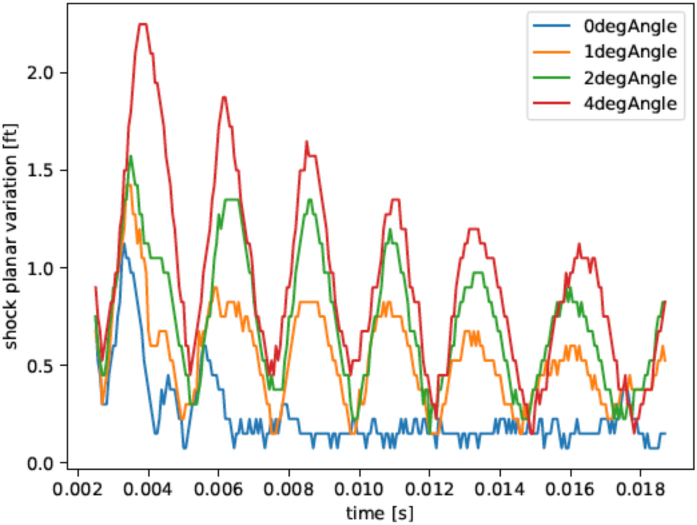
Hang Angle

The HE package is similarly very sensitive to the angle at which it is hung

Table: Simulations with varying counter-clockwise rotations of the high explosives.

Rotation [deg]	Shock Speed [ft/s]	Impulse [psi s]	Peak Pressure [psi]
0	4797	5002	205
1	4872	5001	206
2	4895	4974	204
4	4898	4950	214

Planarity effects of Hang Angle



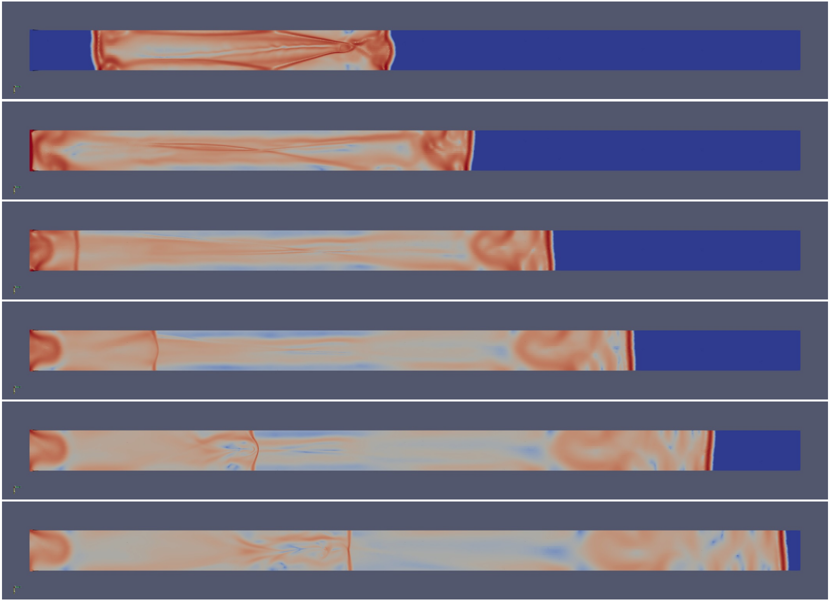


Figure: Snapshots showing density gradients in flowfield from the 1 degree angular rotation simulation.

HE Mass and Atmospheric Density

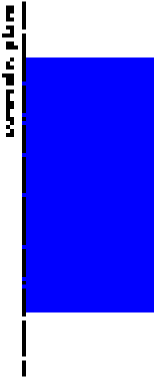
Table: Simulation with varying high explosive weights.

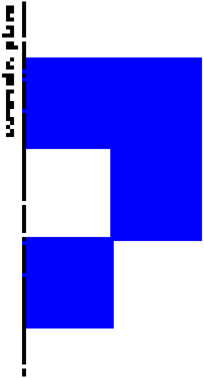
Weight [lbs]	Shock Speed [ft/s]	Impulse [psi s]	Peak Pressure [psi]
190	4797	5002	205
180.5	4698	4809	196
171	4593	4612	187

Table: Reduced atmospheric pressure simulations.

Sim	Atmos Pres [psi]	Atmos Density [lb/ft^3]	Shock Speed [ft/s]	Impulse [psi s]	Peak Pres [psi]
Baseline	11.286	0.0569	4797	5002	205
-.21755 psi	11.069	0.0558	4839	4980	205
-.43511 psi	10.851	0.0547	4879	4958	205

HE Shape





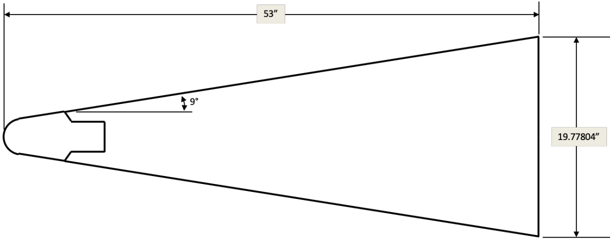
HE shape

Table: Comparison of baseline simulation with the simulation containing the true shape of the explosive.

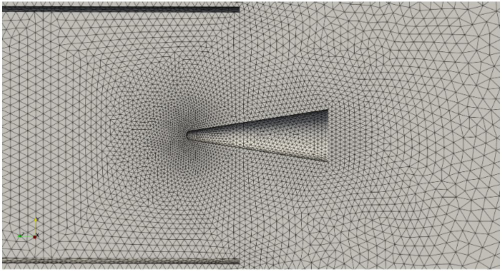
Simulation	Shock Speed [ft/s]	Impulse [psi s]	Peak Pressure [psi]
Baseline	4692	5056	201
True HE Shape	4724	4985	199

Aeroshell Analysis

- Unclassified mock system with fictitious geometry and material properties
  - Weight: 225 lbf
  - Length: 53"
  - Aft radius: 9.89"
- Has an internal payload of mock components, and we have built a model in Abaqus to represent this system.

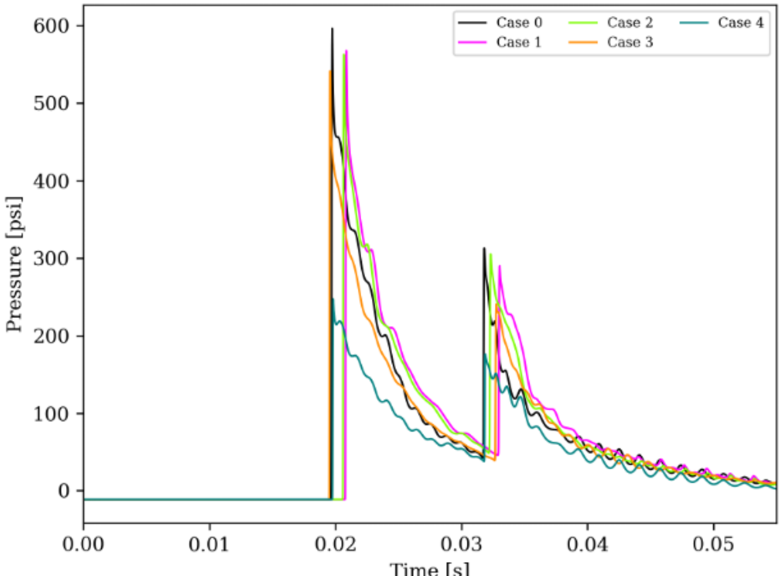


Aeroshell and QUINOA



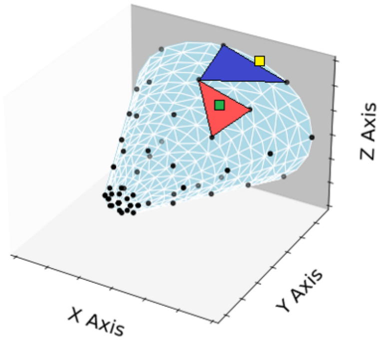
Five parameterized cases were run on the entire geometry in QUINOA, from HE to impact of shock wave over test body.

Case	Angle of Attack	Explosive Mass (lbm)	Explosive Volume	Offset (inches)
0	0	190	2.84 x 2.84 x 408	0
1	0	190	2.84 x 2.84 x 367	6
2	0	171	2.84 x 2.84 x 367	6
3	10	190	2.84 x 2.84 x 408	0
4	22	190	2.84 x 2.84 x 408	0

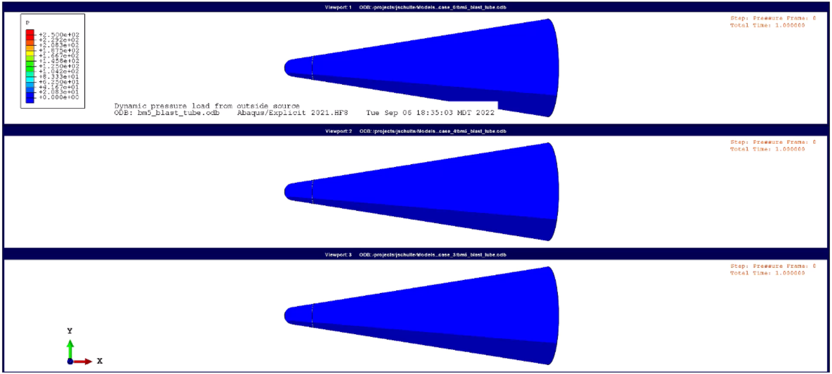

Case 0
Case 1
Case 2
Case 3
Case 4
Pressure [psi]
600
500
400
300
200
100
0
0.00
0.01
0.02
0.03
0.04
0.05
Time [s]

Pressure Mapping

- Probes placed on B5 geometry in Quinoa output pressure history on surface of body for every time step
- Delaunay Triangulation used for probe weighting and mapping pressure history onto Abaqus model
- Normalize time profiles to a common frame to keep the shock time of arrival consistent



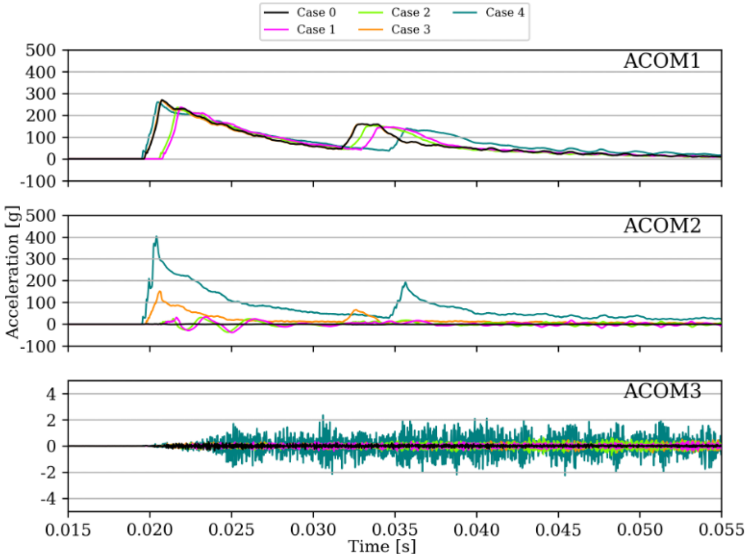
Pressure Mapping



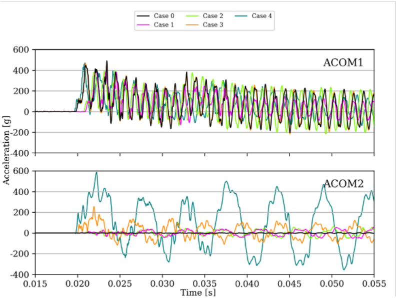
Case 0 (top), Case 3(middle), and Case 5(bottom)

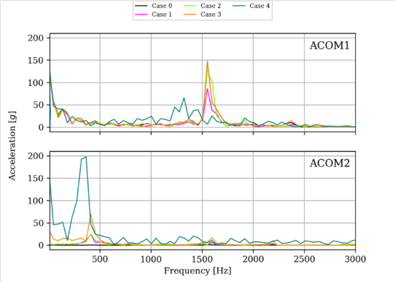
Acceleration results

- Integrated acceleration for the entire system: ACOM1 is Axial, ACOM2 is longitudinal, and ACOM3 is lateral.



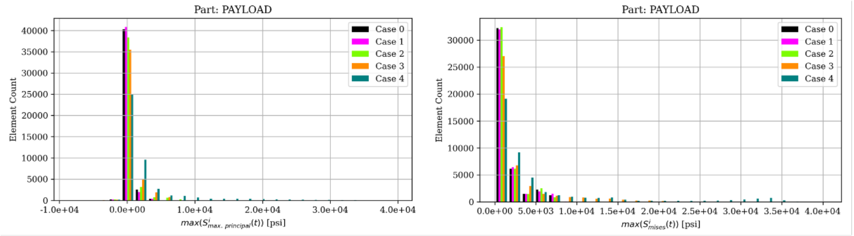
Payload Accelerations





Case 0-3 have distinct modes of axial acceleration at 1600 Hz
Case 4 has a broader spectrum of modes between 500 and 2000 Hz

Payload Accelerations



Principal stress and Von Mises stress element counts. Cases 3-4 show some elements experience von Mises stresses greater than 1.0e4 psi, while cases 0-2 do not.

Conclusions

- A mesh convergence study shows that shock arrival times converge for basic flow shots (No RB)
  - The reflected shock timing may require more advanced simulation capabilities such as a JWL EoS
- Sensitivity study reveals a surprisingly high sensitivity to the placement of the HE package. Bayesian inference tools used on the experimental datasets suggest this is a real effect.
- Sensitivity analysis of ambient conditions such as temperature and pressure reveal minimal effect.
- Porting of pressure data from QUINOA simulations to perform structural analysis on the aeroshell geometry was successful, and shows a strong dependence of payload response to the angle of attack.